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THE UTILITY-SCALE JOINT-VENTURE PROGRAM

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ABSTRACT

The Department of Energy's Utility-Scale Joint-Venture (USJV) Program was developed to help industry commercialize dish/engine electric systems. Sandia National Laboratories developed this program and has placed two contracts, one with Science Applications International Corporation's Energy Projects Division and one with the Cummins Power Generation Company. In this paper we present the designs for the two dish/Stirling systems that are being developed through the USJV Program.

INTRODUCTION

The Utility-Scale Joint-Venture (USJV) Program* is a natural outgrowth of the Department of Energy's Solar Thermal Program over the past fifteen years. During this period, the Solar Thermal Program first demonstrated the performance of a dish/Stirling electric system and set a world's record of 29.4% solar-to-electric conversion efficiency with ADVANCO's Vanguard system [1]. At that time, the DOE recognized that the components, the dishes, thermal receivers,

and engines, were too complex and costly for these systems to produce electric power at a competitive price with conventional power production technologies. Therefore, the Program proceeded to develop advanced dish concentrators and liquid-metal thermal receivers, and to work with Stirling engine manufacturers to *solarize* their engines with the objectives of reducing cost and maintaining high levels of performance. Current activities are aimed at incorporating the technical developments of the last ten years into integrated, complete dish/Stirling systems [2]. Reference 3, written by Stine and Diver, is an excellent overview of the current status of dish/Stirling system development.

The objective of the USJV Program is to help industry develop and market commercial-scale dish/Stirling systems by the start of the twenty-first century. The five key elements of the program are

- The projects are directed at the commercialization of dish/engine systems by the year 2000.
- There is a 50:50 cost share between the industry team and the DOE.
- The projects will last about five years and comprise three phases. The last phase is the production, installation, and test of a 1 MW. plant.
- Utility involvement in the projects is required in all three phases.
- The projects are industry led with support from the national laboratories.

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At this time, two projects have been funded under the USJV Program, one with Science Applications International Corporation's (SAIC) Energy Projects Division in Golden, CO, and one with the Cummins Power Generation, Inc. (CPG) of Columbus, IN. SAIC and CPG have both been funded for Phases I and II of the project (3 years for SAIC and 4 years for CPG) at a total cost of about 18 million dollars each. Following the successful completion of the first two phases of the projects, DOE and the contractors will negotiate new contracts for Phase III. Phase III of the projects is estimated to cost from 15 to 20 million dollars for each. The dish/Stirling systems that are being designed in these two projects are presented in this paper.

THE SAIC DISH/STIRLING SYSTEM

SAIC leads a team comprising Stirling Thermal Motors (STM) and Detroit Diesel Corporation (DDC) of Ann Arbor, MI, and several utility partners. SAIC will provide the systems integration and the solar concentrator (the second-generation faceted stretched-membrane dish). STM will provide their kinematic Stirling engine and will lead the thermal receiver development activities. Detroit Diesel is responsible for designing the *cold short block* parts of the engine for mass production and for manufacture of the short block in later phases of the project.

SAIC's Solar Concentrator

The solar concentrator for SAIC's dish/Stirling system is the second generation of the Faceted Stretched-Membrane (FSM) Dish, which was developed under a DOE/Sandia project [4, 5]. The FSM Dish design has twelve, 3-meter-diameter facets that are covered with 3M's ECP 305 silver-acrylic film. The facet support structure is made from structural steel shapes and balances the weight of the power conversion system at the azimuth drive. The elevation drive is a linear screw jack. The FSM dish is currently under test at Sandia's National

Solar Thermal Test Facility in Albuquerque, NM. Preliminary results show that the dish provides 61.4 kW_t through a 0.50-meter diameter aperture and that the dish has an *equivalent* slope error of 2.8 milliradians (mr.).

The design of SAIC's dish is similar to the Faceted Stretched-Membrane Dish developed in the DOE program. However, several new features have been incorporated into the design. First, the facet support structure has been changed to better accommodate mass production and ease of installation. It now comprises two circumferential ring trusses, which are each made from identical members, and eleven identical radial trusses. Sixteen 2.74-meter diameter facets will be used on the dish increasing the total area by about 6%. The focal length of the dish has also been increased from 9.0 meters for the FSM Dish to 10.0 meters for the second-generation dish. One other design change that SAIC has made is to use thin glass mirrors as the reflective surface in place of the ECP 305 polymer film. The reason for this change is that the projected performance of the glass over the life time of the system is better than the film at the current time. The decision to use glass is purely an economic one.

Two problems that arise from the faceted dish design are the relatively large aperture diameter that it requires and the localized heating of the receiver due to images from each of the facets. By increasing the number of facets from 12 to 16 and also increasing the dish focal length, SAIC is addressing both of these design issues. This was demonstrated when the focal length of the FSM Dish at Sandia was increased to 10.0 meters. For this facet alignment, a total power of 67.9 kW_t was measured for a 0.50-meter diameter aperture. The dish-equivalent slope error for the longer focal length also improved over that at the

shorter focal length and was found to be 2.3 mr.

SAIC's Power Conversion System

The engine for SAIC's dish/Stirling system is the STM 4-120 kinematic Stirling engine, which has been developed by Stirling Thermal Motors. One of the strengths of the SAIC/STM/DDC development team is an agreement between STM and Detroit Diesel to develop the 4-120 for a wide range of applications including a hybrid vehicle and generator sets, as well as the dish/Stirling system. STM brings the Stirling-specific experience and the technology of the 4-120 to the relationship, and DDC brings an understanding of mass production. The STM 4-120 Stirling engine is a four cylinder variable-stroke kinematic Stirling engine. The variable stroke is achieved through the use of a variable-angle swashplate. The engine working fluid is helium. The results of engine testing with natural gas heating show that the power output ranges from 10 kW at 65% of full stroke to 25 kW at 100% with corresponding gross engine efficiency of 40 to 42%. For these tests, the heater-head temperature was 750 °C, the coolant was at 45 °C, and the engine speed was 1800 RPM. To generate electrical power for grid applications, the output shaft of the engine is connected to a high efficiency induction generator.

One of the key components of SAIC's dish/Stirling system is the thermal receiver. The thermal receiver intercepts and absorbs the direct-normal insolation provided by the dish and transfers this heat (approximately 63 kW) to the heater head of the Stirling engine. The baseline receiver for this system is a directly-illuminated tubular receiver similar to the one used on Advanco's Vanguard system [1]. STM is also considering the parallel development of a NaK pool-boiler receiver based on the fundamental development work done at Sandia [6]. In both cases, hybrid receiver

designs that burn natural gas are being developed in response to the dispatchability requirements of the utilities and the system economics.

The Balance of Plant for SAIC's System

The balance of plant for SAIC's dish/Stirling system includes the engine cooling system, the controls, and the power conditioning system. The cooling system for the engine is being developed for STM by the Harrison Division of General Motors. The control system for Phase I of the project will be a programmable logic controller (plc), which will communicate with the engine controller and provide control for the dish and the thermal receiver. SAIC will develop their own controller in Phase II of the project. The power conditioning system is being developed by SAIC. One unique problem is encountered if and when a utility asks a generator to leave the grid. In the case of a dish/Stirling system, the engine will continue to generate power for a period of time. SAIC is considering dissipating the power thermally or storing it in a capacitor bank for later use. The SAIC dish/Stirling system performance specifications are listed in Table 1.

THE CPG DISH/STIRLING SYSTEM

The objective of the CPG USJV Project is to develop a dish/Stirling power system that produces a nominal power of 25+ kW. *net*. The basic approach to achieving this objective is to build upon both the Dish Stirling Joint Venture (DSJV) Project and the Cummins Total Quality System (TQS) expectations. The DSJV Project is a 7.5 kW. dish/Stirling system which CPG has had under development for 2 1/2 years [7]. The DSJV Project provides a great deal of experience that CPG is using in the USJV Project

The Cummins TQS process provides the guidance for the orderly development of the new products in a *Total System* context. The focus of the TQS process is the

introduction of new products that meet or exceed customer expectations.

Table 1.
System Performance Specifications
for the SAIC dish/Stirling System

DESIGN POINT	
Direct Normal Insolation	1000 W/m ²
Ambient Temperature	30 C
Wind Speed	14.2 m/sec
Engine Speed	1800 rpm
Engine Gas Pressure	12 MPa
Heater Tube Temperature	750 to 800 C
PERFORMANCE	
Incident Solar Power	90.2 kW
Reflected Solar Power	85.3 kW
Intercepted Solar Power	78.2 kW
Absorbed Solar Power	62.6 kW
Net Electric Power Output	22.0 kW
System Efficiency	24.4%

The team that CPG has brought together consists of companies and individuals that have extensive experience in their fields. The subsystems and components under development and the responsible companies are: solar concentrator -- WGAssociates of Dallas, TX, and CPG; free piston Stirling engine -- Clever Fellows Innovative Consortium of Troy, NY; hybrid receiver -- Thermacore of Lancaster, PA.

CPG's Solar Concentrator

The solar concentrator typically contributes the largest portion of the overall system cost. Therefore, in order to reduce the concentrator costs as much as possible, the CPG concentrator will be designed from scratch with the manufacturability, reliability, maintainability, and simplicity as driving characteristics. To allow for the possible down-selection to a larger back-up engine, the concentrator in Phase I will be designed to provide ~110 kW_e to the receiver. When the final engine selection is made in Phase II, this power level may be reduced. The baseline concentrator is a post-mounted design with azimuth and

elevation (az/el) drives. The selection of az/el drives has a number of impacts both on the design of the concentrator itself as well as on other system components. The drive allows the concentrator to be mounted closer to the ground, which minimizes wind forces. This drive arrangement also maintains the engine and receiver at the proper orientations so that they can be lubricated via a sump arrangement and so that the sodium return is provided by gravity. The primary design specifications for the concentrator are listed in Table 2.

Table 2.
CPG Solar Concentrator Specifications

PARAMETER	SPECIFICATION
PCS Weight	1150 kg (2500 lb)
Dish f/d	0.6
Reflectivity (Weath./Clean)	92%
Slope Error	2.0 mrad
Defocus Time	<5 sec

The baseline reflective surface for the concentrator consists of glass mirrors placed on metal panels. The panels will be held in place by a truss structure made of thin-walled steel tubing. The glass/metal technology was selected for a number of reasons. The primary driver was O&M costs; this technology will last the 20-year design life of the system, whereas the plastic stretched-membrane facets currently have a 5-year estimated lifetime. In addition, the panel technology allows the reflective surface to be continuous, which reduces the gross area of the dish and minimizes wind loading on the concentrator drives.

The PCS support will be a flat platform at the end of an extension boom. This arrangement will be adaptable for multiple engine configurations; i.e., it allows for the possibility of down-selecting a back-up engine with only minor impact on concentrator design.

CPG's Power Conversion System

The baseline PCS to be employed in the USJV Project consists of a 25+ kW. Stirling engine and hybrid heat pipe receiver. Design parameters for the PCS are presented in Table 3.

Table 3.
CPG Power Conversion System
Specifications

PARAMETER	SPEC.
Gross Electrical Power	25+ kW _e
Heater Head Temp	650 C
Cooler Outlet Temp	60 C
Efficiency	>33%
Heat Pipe Capacity	90 kW _t
Heat Pipe Temp	700 C

The approach is to scale up the 7 kW. Stirling engine being developed in the DSJV Project to a 25+ kW. engine. The engine design is the Clever Fellows Innovative Corporation (CFIC) opposed-twin free-piston Stirling engine with linear alternators. The opposed cylinder design eliminates engine-induced vibrations, minimizes thermal stresses on the heater head, and may allow the use of stainless steel construction. The pressure differential across the power pistons will be maintained by using seal rings; seal rings will also be used on the displacer to separate the hot and cold volumes in the engine. The linear alternator will employ CFIC's STAR™ design.

The heat-pipe receiver, which is being developed by Thermacore and is similar to the receiver used in the DSJV Project [8], will: employ sodium as the working fluid; be 40 to 50 cm in diameter; be made from Haynes Alloy 230; have a hemispherical front surface; and have either a sintered-nickel or metal-felt wick with circumferential arteries and refluxing. The thermal throughput of the heat pipe will be 90 kW_t. In Phase I, the heat pipe will be

solar-only; in Phase II, a hybrid heat pipe will be developed.

The Balance of Plant for CPG's System

The balance of plant for CPG's dish/Stirling system includes the control system and the power conditioning system.

The integrated control system will control both the concentrator, PCS, and power conditioning system. The design will be an evolution of the work in progress for the DSJV Project, which employs personal computer technology; it will include the appropriate enhancements and adaptations for the USJV Project. One enhancement could be the implementation of a distributed control architecture -- this would result in a lower installed cost and lower maintenance costs.

The primary path for power conditioning is the use of a solid state control & conditioning (SSC&C) device that is being prototyped on the DSJV Project for utility grid applications. The design requirements for the power conditioning system will be developed as the power conversion system evolves.

SYSTEM ECONOMICS

SAIC and Cummins Power Generation each have their own unique and proprietary market development plans. Without divulging any confidential information, we note that both of their plans indicate that dish/Stirling systems can be cost competitive with more conventional power generation methods at relatively moderate production rates. Generally stated, these systems should be able to produce electrical power for 6 to 9 cents/kWhr at installed costs ranging from \$1000 to \$1500 per kW.

SUMMARY

We have briefly described the dish/Stirling electric systems that are being developed by two industry teams in a unique, cooperative program with the Department of Energy.

We believe that these systems will be commercially available by the start of the 21st century.

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